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The influence of vibrations on the preferred bass equalization in an audio system

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Summary
Music is often reproduced at high levels, e.g., in clubs, at concerts or in automobiles. Thereby, the sound excites not only the hair cells of the inner ear, but also the surface of the body. Body vibrations above the threshold of perception can be measured even in classical concert halls. It was shown in a previous study, that vibrations of the human body are important for the quality of the concert experience. Another experiment proved that the perceived loudness of low frequency tones is influenced by the presence of vibrations. A tone was perceived as louder, if vibrations were reproduced simultaneously via a seat surface. Therefore, it is assumed that body vibrations might also change the perception of bass intensity in an audio system. This paper discusses the influence of vibrations on the preferred bass level for music reproduction. The question rises whether adding vibration can help to reduce the sound pressure level in order to prevent hearing damage, e.g., in a discotheques.

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1. Introduction

In this paper the term *vibration* will be used for mechanical stimuli, which excite the surface of the body and stimulate the tactile sense. It has been shown in a previous study that vibrations play an important role for our musical experience [1]. In an other study [2] vibrations were found to be able to influence the perceived loudness of a sound at low frequencies. Tones were perceived to be louder when vibrations were reproduced simultaneously via a seat. Because of this cross-modal loudness illusion, it could be expected that the preferred low-frequency equalization of a music signal would also be affected. In other words, the preferred bass level might change under the influence of additional vibrations. Therefore, the listeners' preference for low-frequency audio equalization was measured under the influence of seat vibrations. However, the direction of this effect is not predictable. On the one hand, the subjects could perceive the low-frequency content louder if vibrations are present and therefore reduce the bass amplitude to compensate for this effect. On the other hand, the listeners might expect a higher level of bass because of the vibrations. In this case, the test participants could prefer amplified low-frequency content in the audio signal to better match the vibrations.

2. Setup

To investigate the coupled perception of vibrations and sound, it was necessary to develop a reproduction system that is capable of separately generating vibrations and sound. A surround setup was used according to ITU-R BS.775-1 [3] with five Genelec 8040A loudspeakers and a Genelec 7060B subwoofer. All loudspeakers were placed in ear height on a circle with a diameter of 5 m. The system was equalized to a flat frequency response at the listener position in the center of the room.

Additionally, an electrodynamic shaker (self-made based on an RFT Type 11076 with an Alesis RA 150 amplifier) was applied. Whole-body vibrations were generated vertically as shown in Figure 1. The system was able to reproduce acceleration levels up to 140 dB. The acceleration level L_{acc} is a common measurement unit for vibrations. It is defined as the logarithmic ratio of the rms acceleration a and a reference value $a_0 = 1\,\mu\mathrm{m\,s^{-2}}$

$$L_{\mathrm{acc}} = 20\,\log\frac{a}{a_0}\,\mathrm{dB}.$$

In contrast to sound pressure level, 0 dB acceleration level is not related to the perception threshold. For example, levels above 80 dB are necessary for vertical seat vibrations to be perceivable [4].

Subjects were asked to sit on a flat, hard, wooden seat (46 cm × 46 cm) with both feet flat on the ground. If necessary, plates were placed below the subject's

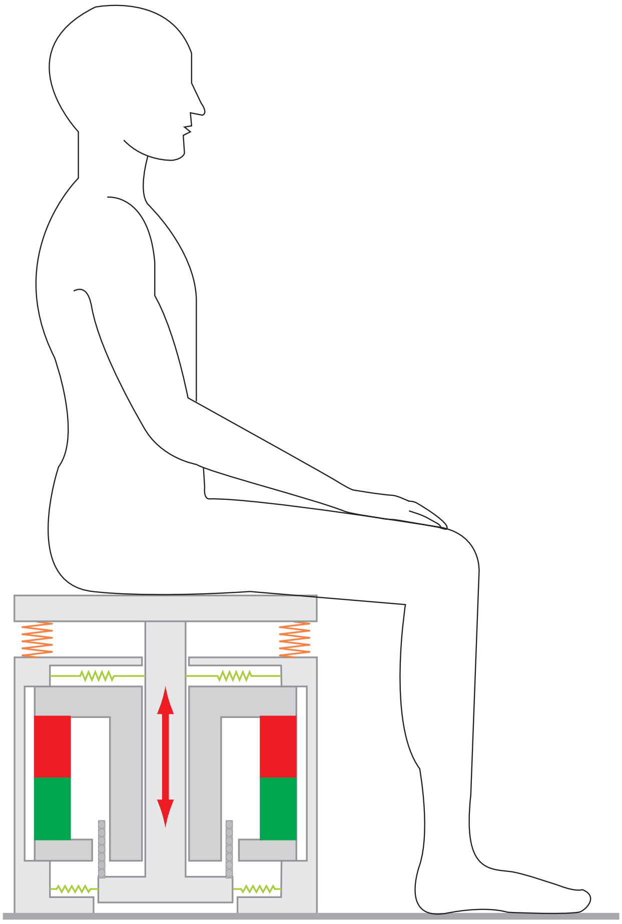

Figure 1. Vibration chair with electrodynamic exciter.

feet. The transfer characteristic of the vibrating chair (acceleration at the surface of the seat versus voltage input) was strongly dependent on the individual person. This phenomenon is referred to as the body-related transfer function (BRTF). Differences up to approximately 10 dB have been measured for different subjects. Taking into account the just noticeable difference in thresholds for vertical seat vibrations, which are approximately 1 dB [5, 6], the individual BRTFs should be compensated for during perceptual investigations. For a detailed discussion, see [7]. The BRTF of each subject was individually monitored and equalized during all experiments. Subjects were instructed not to change their sitting posture after calibration until the end of the experiment. The transfer functions were measured using a vibration pad (Brüel & Kjær Type 4515B) and a Sinus Harmonie Quadro measuring board and compensated using inverse filters in MATLAB. This resulted in a flat frequency response over a broad frequency range (±2 dB from 10 Hz to 1000 Hz). An exemplary BRTF with and without individual compensation can be seen in Figure 2.

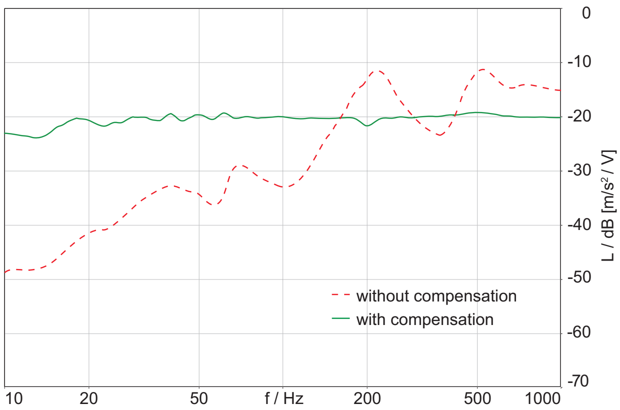

Figure 2. Body-related transfer functions (FFT 65536, 1/24th octave intensity averaging) measured at the seat surface of the vibration chair with and without compensation.

3. Stimuli

To represent typical concert situations for both classical and modern music, four sequences were selected from music DVDs [8, 9, 10, 11] that include low-frequency content. A stimulus length of at least 1:30 minutes was chosen to ensure that the participants had sufficient time for their evaluations. The following sequences were selected:

- Bach, Toccata in D minor (*church organ*)
- Verdi, Messa Da Requiem, Dies Irae (*kettledrum, contrabass*)
- Dvořák, Slavonic Dance No. 2 in E minor, Op. 72 (*contrabass*)
- Blue Man Group, The Complex, Sing Along (*electric bass, percussion, kick drum*)

The first piece, Toccata in D minor (BWV 565), will be referred to as BACH. A spectrogram of the first 60 s is plotted in Figure 3. A rising and falling succession of notes covering a broad frequency range can be seen in the figure. Additionally, steady-state tones dominate the composition. Strong vibrations would be expected in a church for this piece of music containing low-frequency notes played with the pedal of the organ [12].

The second sequence, Dies Irae, will be abbreviated as VERDI. It is a dramatic composition for double choir and orchestra. The excerpt starts with the beginning of the second section of the requiem and was truncated after 1:30 minutes. A partial spectrogram is plotted in Figure 4. Impulsive fortissimo sections with a concert bass drum, a kettledrum, and tutti orchestra alternate quickly with sections that are dominated by the choir, bowed instruments, and brass winds. The sequence is characterized by strong transients.

The third stimuli, Slavonic Dance No. 2 in E minor, will be referred to as DVORAK. The selected

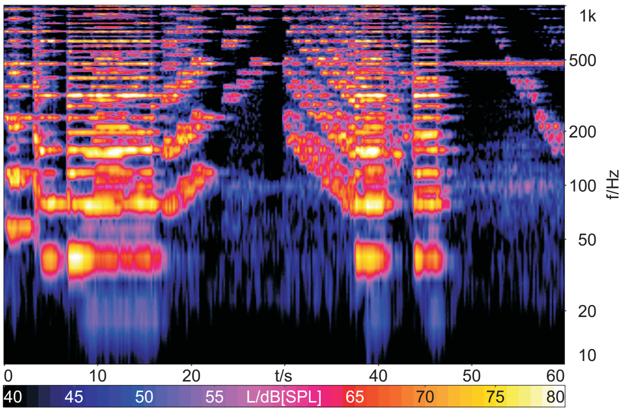

Figure 3. Spectrogram of the mono sums for 60 s from the BACH sequence. The short-time Fourier transforms (STFTs) were calculated with 8192 samples using 50% overlapping Hanning windows.

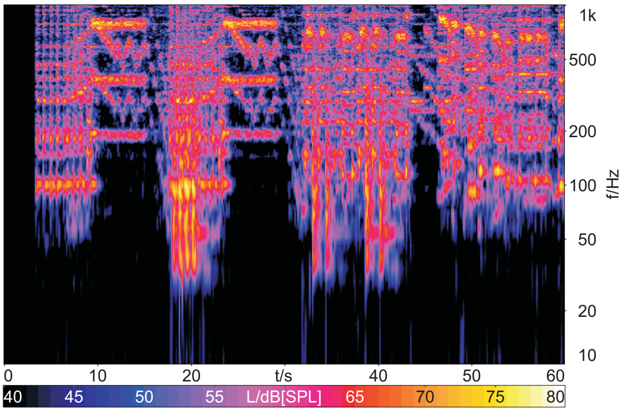

Figure 4. Spectrogram (STFTs 8192 samples, 50% overlapping Hanning windows) of the mono sums for 60 s from the VERDI sequence.

sequence includes the first 1:30 minutes of the composition. Again, a spectrogram is plotted in Figure 5. It is a calm orchestral piece, dominated by bowed and plucked strings. Contrabasses and cellos continuously generate low frequencies at a low level.

An organ work and two orchestral compositions with transient and steady-state content at low frequencies have been described thus far. The fourth and final sequence, Sing Along, is a typical pop music example. It is performed by the Blue Man Group, which will be further shortened to BMG. The sequence starts at 32:24 on the DVD and lasts 1:30 minutes. It is characterized by the heavy use of drums and percussion. These generate transient content at low frequencies, which can be seen in the corresponding spectrogram in Figure 6. Additionally, a bass line can be easily identified.

The sequences were played back using the 5.1 surround setup described above. The loudness of the four sequences was equalized in a pilot experiment using three subjects. The resulting equivalent continuous sound pressure level was measured; for instance, a value of approximately 75 dB was obtained for the BACH sequence. Additionally, vibration signals were generated from the audio sequences using a 100 Hz low-pass filter (Butterworth, 10th order) and reproduced via the vibration seat. Different intensities were presented in different trials. The subjects were not allowed to adjust the vibration magnitude.

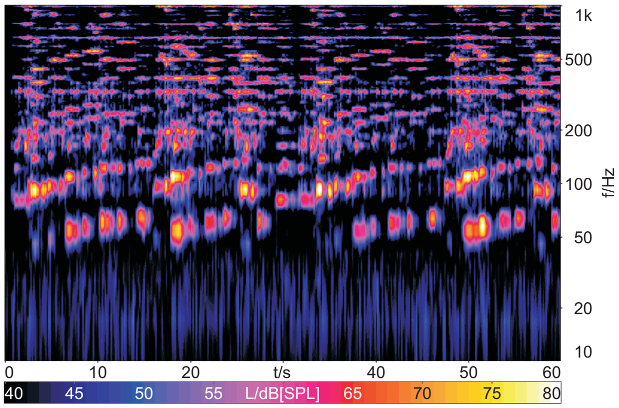

Figure 5. Spectrogram (STFTs 8192 samples, 50% overlapping Hanning windows) of the mono sums for 60 s from the DVORAK sequence.

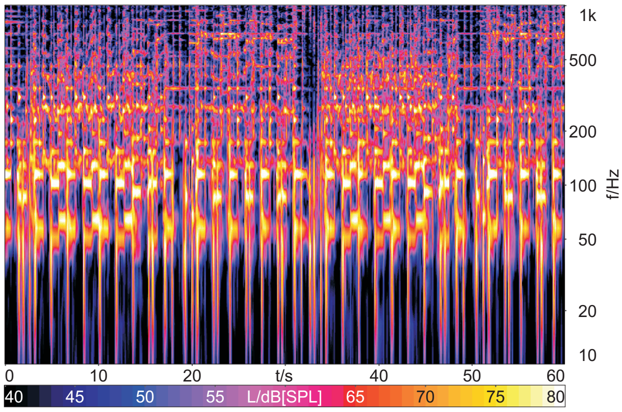

Figure 6. Spectrogram (STFTs 8192 samples, 50% overlapping Hanning windows) of the mono sums for 60 s from the BMG sequence.

4. Subjects

A total of 20 subjects participated in the experiment (16 male and 4 female). They were between 19 and 49 years old (mean 25 years) and between 50 and 115 kg (mean 73 kg). All participants stated that they had no known hearing or spine damage. Most of the test subjects had never participated in a listening experiment before. In general, the listeners can be regarded as naive, with no background in audio engineering or sound evaluation.

5. Experimental Design

The bass signal was derived from the mono sum of the 5.1 audio signal using a steep cross-over filter at 100 Hz (Butterworth, 10th order) and was reproduced via a subwoofer. The task of the subjects was to adjust the intensity of the bass (not the vibration magnitude) to their preferred level using an infinite rotary knob with no visible marks. Intensity increments were possible in 1 dB steps over a 25 dB range. The initial bass level in each trial was randomly varied over the complete dynamic range.

The listeners were asked to adjust the bass equalization for four different levels of seat vibrations. The acceleration levels referred to the individual perception threshold to ensure that the perceived vibration magnitude was comparable between subjects. The thresholds of vibration perception were measured at 25 and 50 Hz. Because the threshold for vertical seat vibrations is rather flat below 100 Hz [4], an averaged perception threshold was calculated from the two measurements for each participant. The four acceleration levels were then adjusted relative to the individual thresholds and were further labeled as follows: none; low (0 dB); medium (6 dB); and high (12 dB). The low-vibration setting was just perceptible, with an *averaged* acceleration level equal to the perception threshold. This level corresponds to a *peak* acceleration level between 4 and 10 dB greater than the threshold depending on the music sequence.

To test the reliability of each subject, there were two repetitions of each sequence. This process resulted in a total of 32 trials (four sequences × four vibration levels × two repetitions). The listeners were allowed to stop a trial as soon as they were satisfied with their adjustment. Before the experimental session, the listeners were familiarized with the procedure and all of the music sequences. The overall test time varied between subjects and took up to 1:30 h. All of the stimuli were presented in completely random order.

6. Results and Discussion

The results were analyzed with a repeated-measures ANOVA. The preferred bass equalization in the no vibration condition (reference) was dependent on the individual subject and music sequence. In general, the listeners preferred higher bass levels compared to a flat frequency response. The standard deviation for the two repetitions was approximately 4 dB, which appears quite small for naive listeners, considering that the repetitions were randomized within the entire experimental session, including various conditions with vibrations. Figure 7 presents the mean preferred bass equalization levels for different vibration levels relative to the preferred bass levels without vibrations. It can be seen that the vibrations had no significant effects on the preferred bass equalization. This finding was true for all vibration levels. The results support neither the hypothesis that subjects would correct for increased loudness due to vibrations nor the hypothesis that subjects would increase the bass level because they expected more low-frequency content due to vibrations. Furthermore, no preference groups were observed.

One could argue that the cross-modal loudness illusion [2] is relatively small (approximately 1 dB) and seems to be independent of vibration level. Therefore, only a negligible effect could have been expected in this experiment. However, in the original loudness illusion experiment, very short 1 s sinusoids were compared with each other in an A-B design. The test participants were aware of the added vibrations and were told to focus solely on the loudness of the two tones. Therefore, the experiment might have underestimated the increased loudness in a more realistic scenario. Interestingly, the subjects reported perceiving the bass more intensely with vibrations present during the current experiment. This finding supports the hypothesis of increased loudness because of the vibrations. However, the more intense bass might fit well with the expectation of an amplified bass if vibrations are present. This theory could explain the consistent bass equalization preferences in the results.

The results indicated that the presence of seat vibrations did not affect the preferred bass equalization of naive listeners. In contrast, two other studies reported that vibrations associated with low-frequency reproduction of music in an automotive audio system produced a decrease in the level of preferred bass equalization. Data from Simon et al. [13] and Martens et al. [14] are plotted in Figure 8 for comparison.

Both studies investigated the same automotive audio system via binaural reproduction using head-

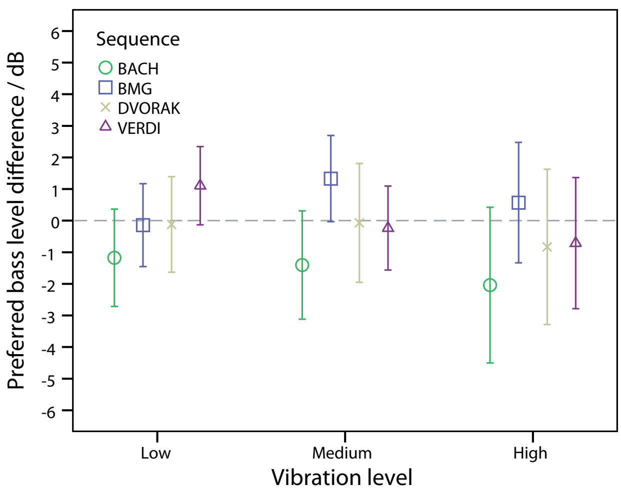

Figure 7. Mean preferred bass equalization levels with 95 % confidence intervals for different vibration levels. The bass level is plotted relative to the individual preferred bass level without vibrations.

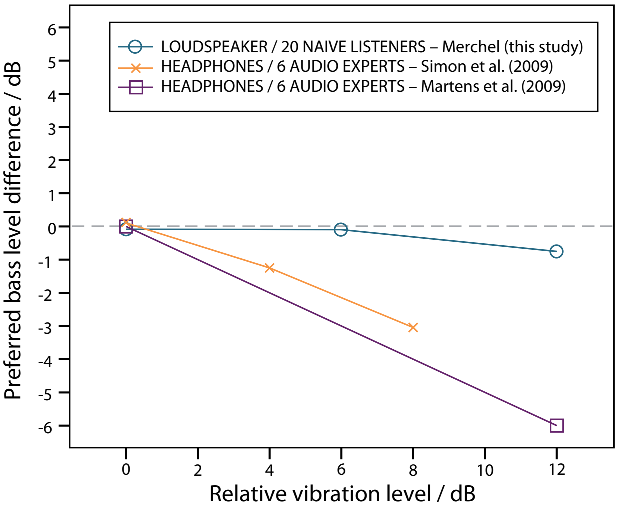

Figure 8. Comparison of the relative preferred bass equalization levels from this study and from two other studies [13, 14] for different vibration levels relative to the threshold of perception.

phones. Martens et al. [14] generated vibrations using a platform in a room. An adaptive staircase tracking procedure was applied for bass adjustment. Short audio segments were selected from four musical sequences. Simon et al. [13] simulated vibrations by mounting a low-frequency audio transducer under the seat of a car. The test procedure was similar to that applied in this study. Two looped audio sequences were chosen with lengths of 20–30 s. Both studies used trained listeners with backgrounds in audio evaluation. The vibration generation approaches appeared to be similar to the approach applied in this study.

The data from both studies agree with a 1.5–2 dB decrease in the preferred bass level for a 4 dB increase in vibration level. At low vibration levels near the threshold (0 dB), no apparent effects were observed in any of the studies. The differences from the current results at higher relative vibration levels cannot be explained definitively. The studies differed in reproduced musical genres, with mainly classical programs in this study and with no orchestral or sacral music in the others. However, no significant differences were observed between musical genres in this study. Furthermore, the number and selection of subjects might have played a role. Audio experts could have different preferences than naive listeners. Additionally, reproduction via headphones might be important. The 'missing 6 dB' effect with headphones, which was partially related to the absence of tactile stimulation [15], might have been compensated for through the reproduction of vibrations. Martens et al. reported that the inclusion of vibrations at low levels improved the similarity between binaural reproduction and the in situ experience in the car. However, at higher vibration levels, the audio experts might have become annoyed and 'reduced the level of bass equalization, perhaps with the false hope that it might also reduce the vibration' [14]. This result would have biased the effects, resulting in lower preferred bass levels. In any case, the effects of vibrations on bass equalization preference cannot be conclusively reported. Further experiments are needed to investigate the effects of reproduction method, audio properties or listener background.

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